Recent Progresses in Seismic Study on High Arch Dam in China

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ABSTRACT :

In this paper some recent research progresses achieved by the team supported by Chinese National Science Foundation including seismic input, structural responses and dynamic resistance as the mutually coordinated factors necessary for seismic safety assessment for high arch dams are briefly introduced. For seismic input, a new method of generating artificial accelerogram non-stationary both in amplitude and frequency and a more reasonable "finite fault method" to assess the Maximum Credible Earthquake (MCE) deterministically for dam site near the causative fault are stressed. For structural responses, an improved analysis of arch dams simultaneously considering all the factors such as: dynamic interaction of dam-foundation-reservoir, radiation damping of energy dispersion in far-field foundation, topography features and geological disturbances including all potential sliding blocks of arch dam abutments at both banks within the near-field foundation adjacent to dam, opening and slipping of contraction joints within dam and along the abutment sliding surfaces and dam base periphery during strong earthquake, and spatial variation of seismic input along dam foundation is developed. Also, a new conception from the break point of displacement responses of the integral dam-foundation-reservoir system under seismic action as the quantitative criterion for evaluating arch dam breach is suggested. For dynamic resistance of dam concrete, the effects of static preloads on the dynamic behavior of fully-graded dam concrete are investigated by testing, and the results are explained by the three-dimensional meso-mechanics analysis of the concrete specimen with real mix proportion. The dynamic failure mechanism revealed by the analysis was also observed by the X-ray computed topography (CT) technique. Finally, the high-performance parallel computation technique was successfully used in all these analyses.

KEYWORDS: high arch dam; seismic input; response analysis; dynamic behavior of dam concrete; parallel computation

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1. INTRODUCTION

Recently, a series of critical hydropower projects with arch dam of about 300m high are being under construction and will be constructed in the severe seismic regions of western China. The seismic safety assessment of those projects is deeply concerned over by the authorities and designers of projects as well as the society. The seismic input, structural response and dynamic resistance are the three mutually coordinated factors necessary for the assessment. Some recent progresses in all this three aspects achieved by the author's team supported by the National Science Foundation of China during the upsurge of hydropower construction in China are briefly introduced in this paper.

2. SITE-SPECIFIC SEISMIC INPUT AT DAM SITE

As commonly recognized, the PGA has a lack of predictability in the near-field which is more important for high dam in severe seismic area, and its pulse peak with high frequencies is of little engineering significance to the responses of high dams. So, it is recommended that the seismic hazard evaluation for dam site is based on the response spectrum related 'effective peak acceleration (EPA)' instead of the current used 'peak ground acceleration PGA'. By analyzing a series of acceleration records at rock sites of events with different magnitude and epicenter distance intervals in the western United States, an average normalized spectral with its peak at period 0.2 second and an amplification factor of 2.5 is revealed. So, the EPA is defined as the spectral acceleration at period 0.2 second divided by an average amplification factor of 2.5.

The 'equal-hazard spectra' usually used as design response spectra do not reflect the physical characteristics of response spectrum of a real earthquake associated with the actual magnitude and distance. So, the spectrum from a scenario earthquake as a site-specific design response spectrum for dam is suggested. Among all earthquakes with the magnitude (M) consistent with the design EPA at dam site, the scenario earthquake is selected with a maximum probability of occurrence and a distance (R) usually nearest to the dam site along the major fault within the more critical potential seismic source. Then the spectrum can be defined from the M and R by using an appropriate attenuation relationship [1].

Earthquake ground motions are strong stochastic processes, non-stationary both in time and frequency domains. However, the influence of the non-stationary in frequency content is usually overlooked, but it may significantly affect on the responses of nonlinear structures like high arch dams during strong earthquakes. Therefore, based on the Priestley's theory of evolutionary power spectra [2], an approach of generating artificial accelerograms non-stationary both in amplitude and frequency and consistent with target evolutionary spectrum is proposed [3]. In this method the evolutionary power spectra are calculated by Nakayama's method [4]. The target evolutionary spectra are developed based on 80 accelerograms at rock foundation from western United States with magnitudes $M \geqslant 6.4$ and epicenter distances $R<45$ km, from which the statistical prediction models for given M and R are established using regression equations similar to that proposed by Hisao Goto [5].

In comparison with the approach developed by Kameda based on evolutionary spectrum calculated by using multi-filter technique [6], its problem of the damping factor selection can be avoided and the time-dependent characteristic of phase angle can also be considered in the proposed approach.

Fig. 1 shows the regressed target evolutionary spectrum for M=7.0 and R=15km and the generated artificial accelerogram related to it

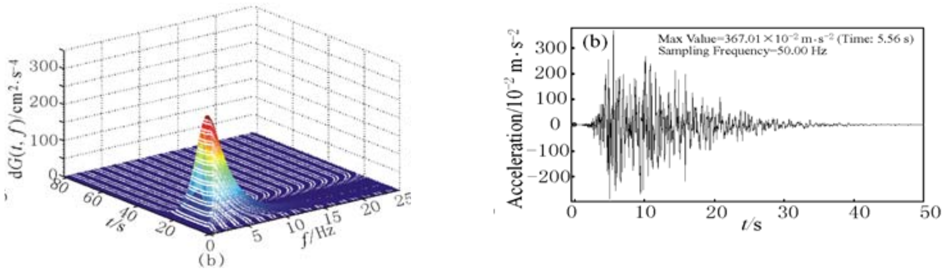


Fig.1 Target evolutionary spectrum for M=7.0 and R=15km and generated artificial accelerogram

The maximum design earthquakes for a good few high arch dams in China are near the causative fault with rather high magnitude. In such case there are two fatal weaknesses significantly affecting on the seismic input at dam site. The first one is that the earthquakes have still been regarded as a point seismic source, while for such an earthquake with magnitude and distance of more than 6.5 and 30km respectively, actually, a 3-dimensional spatial area source of near fault should be used. The second one is that the strong motion records used to get regression of the attenuation relationships mainly based on the limited accelerograms recorded at rock sites with magnitudes less than 7 and distances between 10km to 100km. Their extrapolation to the events with very small probability of exceedance of maximum design earthquakes of dams becomes rather uncertain. Besides, the rupture directivity and the hanging wall effect for near field strong ground motion also can not be considered in the seismic hazard evaluation Therefore, using the deterministic “finite faults method” to synthesize directly the design accelerograms is recommended. In this method the major active fault of the critical potential seismic source is divided into a series of sub-faults as point sources with provided mode, rate, and time sequence of the rupture. By accumulating the effects of each point source on the dam site in sequence, the strong ground motion near faults at the dam site can be directly predicted. Of course, all the fault parameters, e. g., strike, dip directivity, dip angle ,rupture area and its length, width, as well as the average slip over the fault should be estimated theoretically or semi-empirically. The further study should be focused on the slip model describing the heterogeneity of slip on the fault surface with asperities and the calibration of all the fault parameters related with seismic moment based on the data base of the interpolate earthquakes in China.

Fig.2 shows the synthesized accelerograms for a hydropower project by the stochastic finite faults method and their response spectra which are quite similar to that from the probabilistic method [7].

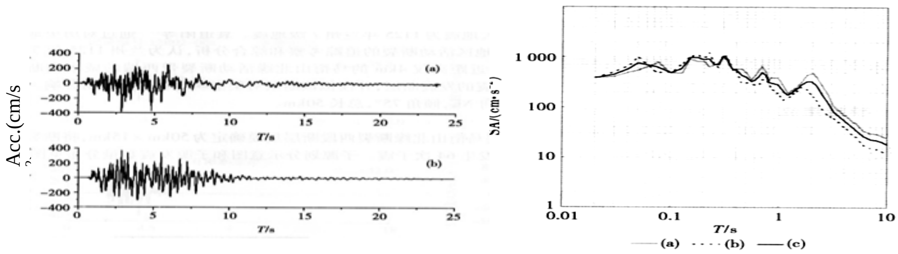


Fig. 2 Synthesized accelerograms by stochastic finite faults method and their response spectra

3. SEISMIC RESPONSES OF ARCH DAM-FOUNDATION- RESERVOIR SYSTEM

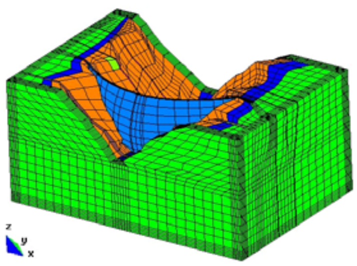
An improved numerical model of dam-foundation-reservoir system more closed to the reality has been developed. In the model all critical factors are considered simultaneously, such as: the dynamic interaction of the dam-foundation-reservoir, the opening and slipping of contraction joints within dam during strong earthquake, mass and material damping of the rock as well as the topography features and geological disturbances including all potential sliding blocks of dam abutments at rock foundation on canyon banks within the near-field foundation adjacent to dam, radiation damping of energy dispersion in far-field foundation, and spatial variation of seismic input along dam foundation are developed. The model of the whole system is discrete in space by finite elements and in time by central finite-differences. The 3-components of the design ground motion are specified along the base of artificial transmitting boundaries, so the spatial variation of seismic input along the canyon can be considered. Its equation of motion is solved as a wave propagation problem by explicit integration in time domain [8] [9]. The procedure of seismic analysis of arch dam system includes three loading cases accomplished successively as follows:

(1) In case 1, the dam elements were treated as dead elements with zero degree of freedom for nodes and only the dead load of the foundation rock is considered in the analysis. At the end of calculation, the initial normal compressive force along the contact planes was modified by adding the calculated contact force. All other states of the foundation were recovered to that before loading.

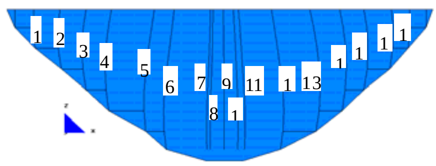
(2) In case 2, the dead load of dam and other static actions including water pressure, silt pressure, and temperature applied to the dam as well as the seepage pressure in the foundation are considered.

(3) In case 3, a three-component seismic input is applied to the base of the artificial transmitting boundaries in form of displacement ground motion, or to the spring-viscous boundaries with free field input including boundary stresses, velocities and displacements.

As the nonlinear dynamic analyses of the system lead to tremendous computer storage capacity and computation time, the high-performance parallel computation technique is used for the analyses based on a LENOVO 1800 PC cluster parallel computation device of 6 nodes each with double CPU in IWHR. The opened developing environment of parallel finite element programs based on the Parallel Finite Element Program Generator (PFEPG) developed by Liang Guoping [10] is developed [11].The strategy of the PFEPG is the program design in basis of component technique and the technique of automatically generating programs. According to the characteristics of domain decomposition method, a finite element program is generally decomposed to six modules：preprocess partition、start、bft、solv、E and U programs, in which the subroutines of E and U component are generated by the FEPG system based on the scripts (VDE or PDE）of the partial differential equation describing the physical fields and the corresponding computational algorithms (NFE), other else components are fixed and provided by the FEPG Library. In the scripts such as VDE and NFE, GCN and GIO for the proposed iteration algorithm are written according to the grammar rules of PFEPG, and then the parallel computational programs of finite element of the analyses can be generated by PFEPG according to the scripts mentioned above. Parallel solvers can be chosen from PFEPG. In case of dynamic analyses of arch dams, the program for artificial transmitting boundary must be inserted and handled in the master node of the cluster computer. To solve the equation within the inner zone is carried out by all slave nodes in parallel with each other. Using the developed parallel program and the analytical procedure mentioned above, the seismic responses of the Xiaowan arch dam of 295m high were analyzed with the model including 17 contraction joints within the dam as shown in Fig.3. Fig.4 indicates the opening of some typical contraction joints at upstream and downstream crest points, which seems not as significant as to damage the sealing compounds near the upstream dam surface.



(a) Finite element mesh



(b) Distribution of contraction joints

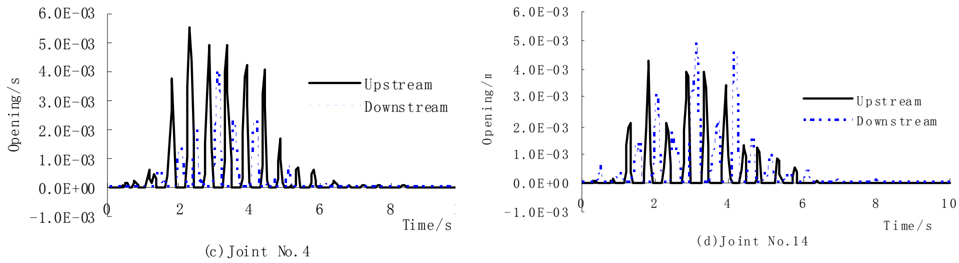


Fig.4 Contraction joint opening at upstream and downstream crest points of joints 4 and 11

The traditional approach of limit equilibrium method widely used in dam engineering for stability analysis of arch dam abutment block as a rigid body detached from the dam is unable to consider the deformation and dynamic interaction between the dam and foundation as well as the dynamic effects of the canyon banks during earthquake. It is essentially is a time-independent static method caused the results far from the real dynamic stability behavior of the integral dam-foundation-reservoir system. Now a new conception from the break point of displacement responses of the integral dam-foundation-reservoir system under seismic action as the quantitative criterion for evaluating arch dam breach is suggested, and it can be implemented using the abovementioned numerical model of dynamic analysis of the integral system in time domain. Fig.5 shows the overload limit state with suddenly change of displacement of Xiaowan arch dam of 295m high.

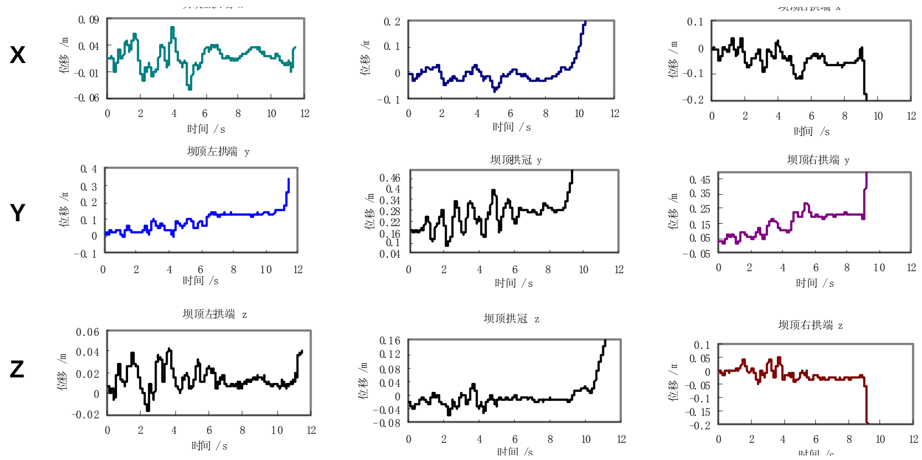


Fig.5 Overload limit state with break point of displacement response of Xiaowan arch dam (H=295m)

4. DYNAMIC RESISTANCE OF DAM CONCRETE

Up to now the dynamic strength of dam concrete used in seismic design has mainly relied on the test of small wet sieving specimens with aggregate bigger than 40mm screened out and under pure dynamic loading without static preloading. Actually, three-graded or four-graded aggregate concrete is always used for dam construction, and dam is always subjected to earthquake while being in operation under static loads. But there is a shortage of dynamic test for fully-graded dam concrete, and the effect of existed static preloads on its dynamic behavior has usually been overlooked.

Recently, a series of dynamic tests of flexural-tensile properties of dam concrete essential for seismic design of arch dams have been carried out. The results reveal that under seismic actions the rate of increment of dynamic flexural-tensile strength in comparison with that under static loading increases with the static preloads. It seems to be explained that the dynamic strength might grow with the static preload if whose intensified rate effect outweighs its damage consequence.

In order to verify the assumption, a three-dimensional non-linear dynamic analysis for the concrete specimen by using meso-mechanics was carried out. As a composite material the concrete specimen consists of differently sized aggregates, mortar, and their interfacial transition zones satisfying the actual proportion requirement of dam concrete. Random distribution both for multi-graded aggregates and the properties of aggregate, mortar and their interfacial transition zones using Monte Carlo method together with a damage variable function and the strain rate effect were considered in the analysis. The finite element mesh of the meso-mechanics analysis is demonstrated in Fig.6. The experimental results are reasonable explained by the analytical procedure as shown in Fig.7. Also, the high-performance parallel computation technique was successfully used in the meso-mechanics analyses of concrete specimens.

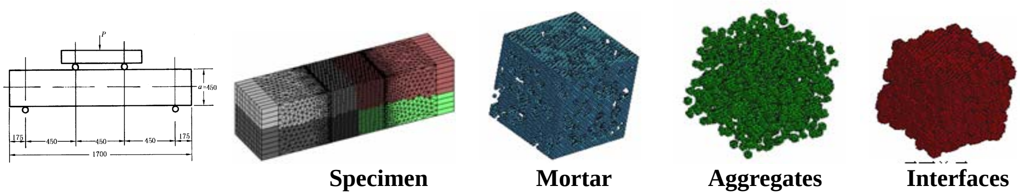


Fig.6 Meso-mechanics model and F.E. mesh of mortar, aggregates and their interfaces

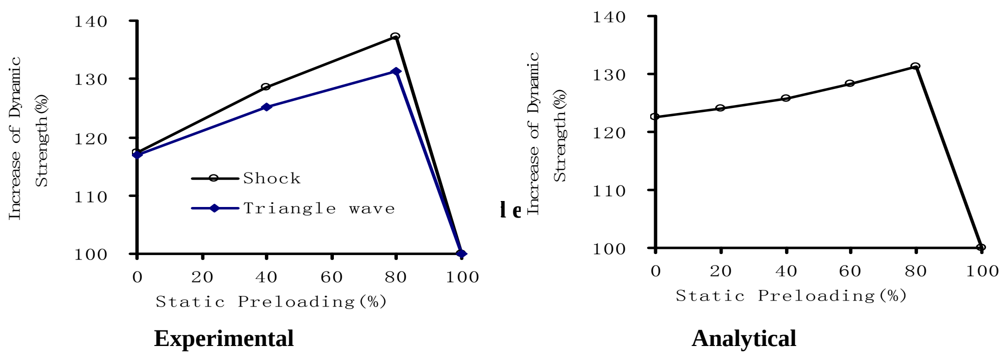


Fig.7 Comparison of the preloaded experimental and analytical results

Besides, the acoustic emission test was also carried out during dynamic tests. Fig. 8 shows the AE counts of specimen in the whole process of static axial tension test and the Kaiser effect under dynamic loading. Obviously, there are no any AE counts during load-off. However, once the concrete is loaded up to about 80% of its ultimate strength, the damage expends automatically even the load keep unchanged and the Kaiser effect disappears.

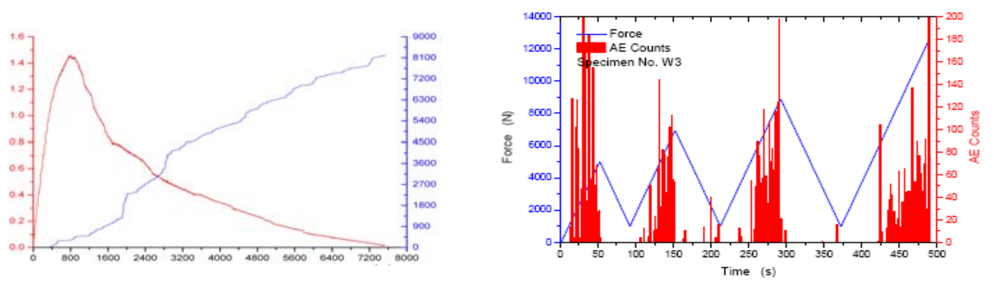


Fig. 8 AE counts of specimen in axial tension test and the Kaiser effect under dynamic loading

Furthermore, in order to investigate the fracture evolution process of inner structure of dam concrete under dynamic loading, the X-ray computed topography (CT) technique has been applied. Cracks in CT images were distinguished and their morphology characters were analyzed based on CT physic theory and image processing technique. The difference of cracking process between the static and dynamic compression loading conditions was investigated in detail. In order to intuitively demonstrate the crack morphology character and crack evolution process during the loading, the formation of 3D images and the animated cartoons displaying technique of the crack development by using the CT test results have been completed using 3DMAX software.Fig.9 shows the comparison of the CT images of concrete with different strain rates [12].The more cracks are revealed the higher strain rate.

Right now a portable test device for dynamic tensile and compressive loading specially designed to fit the conventional medical CT scanner has been manufactured.

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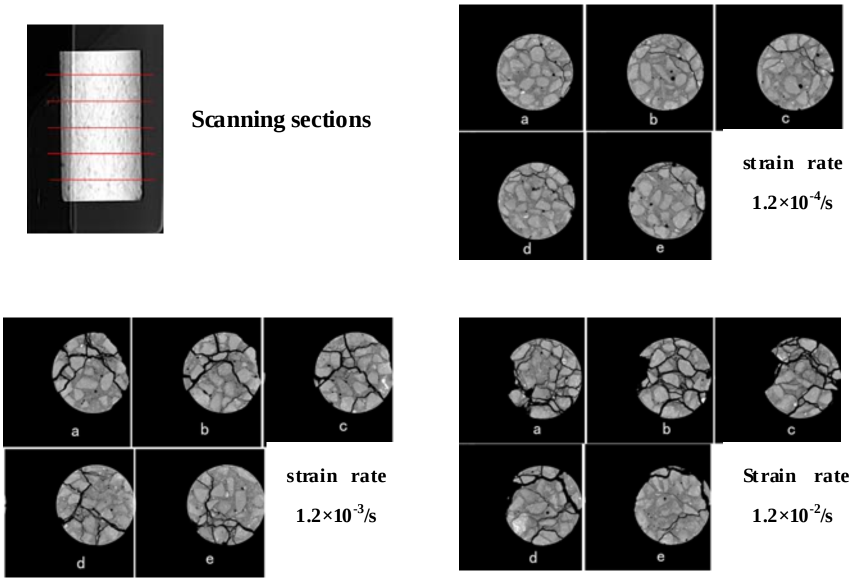

Fig.9 Comparison of the CT images of concrete with different strain rates

5. CONCLUSIONS

(1) It seems more reasonable to use proposed method for generating artificial accelerogram non-stationary both in amplitude and frequency and the “finite faults method” for directly synthesizing the input accelerograms at dam site for MCE.

(2) A criterion for quantitatively evaluating arch dam breach during strong earthquake based on the break point of seismic displacement responses of the integral dam-foundation-reservoir system with consideration of all actual conditions may be more closed to the realities.

(3) The dynamic properties and failure mechanism of dam concrete with full-graded specimens by dynamic tests and analysis using 3-dimentional meso-mechanics model with CT technique verifications deserve great attention and further study.

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